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**Research Paper**

# Digital Standards and Interoperability for Energy-Efficient Smart Building Renovations in Nigeria: The Pathway for Renewable Energy Integration

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***ABSTRACT:*** *Digital standards and interoperability are reshaping construction practices by providing accurate digital representation and supporting lifecycle energy efficiency in building renovation projects. In Nigeria, where urbanization, energy insecurity, and fragmented construction processes persist, the application of standardized digital frameworks offers a pathway for integrating renewable energy systems into smart building renovations. This study investigates the critical enablers and barriers to renewable energy integration in Nigerian renovations, with emphasis on how interoperable digital protocols can enhance collaboration, sustainability, and performance outcomes. A* ***mixed-methods approach*** *was employed, combining a systematic literature review with empirical data collected through a structured survey of* ***150 construction professionals*** *(Architects, Engineers, Project Managers, Contractors, and Energy Consultants) across Nigeria's 10 largest cities. Quantitative analysis incorporated descriptive statistics, the* ***Shapiro-Wilk test*** *(confirming non-normal data distribution, $p < 0.05$),* ***normalized mean ranking***, ***quartile analysis***, *and* ***Spearman's correlation***, *while qualitative insights were derived from thematic analysis. The findings highlight* ***16 critical factors*** *influencing renewable energy integration. Across all professional groups,* ***Stakeholder Coordination (NV = 0.98)*** *and* ***Standardized Digital Protocol Adoption (NV = 0.97)*** *emerged as the highest-ranked enablers, closely followed by* ***Lifecycle Energy Performance (NV = 0.96)*** *and* ***Renewable Energy Integration readiness (NV = 0.96)***. *Quartile analysis positioned these four factors in the upper quartile, underscoring their systemic importance. Correlation analysis further revealed a* ***moderate association ($r_s = 0.634$)*** *between stakeholder coordination and communication efficiency, reaffirming the interdependence of collaboration and information flow. Conversely, contextual disparities were identified: for example, contractors consistently undervalued IT infrastructure adequacy compared to engineers and project managers ($p < 0.05$). This study demonstrates that applying interoperable digital standards significantly enhances renewable energy integration by improving stakeholder collaboration, ensuring compliance with sustainability frameworks, and strengthening lifecycle energy performance monitoring. The results advocate for* ***early institutional adoption of digital standards*** *supported by targeted training, robust IT infrastructure, and regulatory alignment with Nigeria's Energy Transition Plan. By addressing fragmentation through interoperability, Nigeria can accelerate its pathway toward energy-efficient, resilient, and future-ready building renovations.*

***KEYWORDS:*** *Smart Building, Digital Standards, Building renovation, Renewable Energy, Nigeria*

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## I. INTRODUCTION

The global construction industry faces a pressing imperative to embrace both digital transformation and sustainability. Buildings are among the largest energy consumers, accounting for approximately 36% of global energy use and 39% of $CO_2$ emissions (Zhong et al., 2021). Existing building stock offers huge potential for energy savings through renovation rather than new construction (Ruggieri et al., 2023). However, current renovation practices in many countries remain inefficient, fragmented, and unsustainable.

In response, digital standards and interoperability have emerged as catalysts for transformation enabling better collaboration, integration of renewable energy systems, lifecycle performance tracking, and waste reduction (Apata, 2024). Through standardized data models and interoperable protocols, stakeholders can coordinate more effectively, reduce resource waste, and optimize energy use a global trend gaining traction across Europe and North America.

Yet, in many emerging economies including Nigeria, the construction industry lags behind in adopting digital standards. Despite notable benefits, such as improved project delivery, reduced costs, and enhanced productivity through Building Information Modeling (BIM), adoption remains low, constrained by weak regulations, limited technical capacity, and fragmented stakeholder engagement (Wang et al., 2021).

This is particularly critical in Nigeria the continent's largest economy where energy access remains intermittent, and renewable energy contributes less than 20% of the national energy mix. In alignment with its Energy Transition Plan, Nigeria aims to raise renewable energy's share to 30% by 2030 and 60% by 2060, yet building renovation practices currently impede progress (Ogungbemi et al., 2025; Olujobi et al., 2023). Without improved digital infrastructure and standards, the renovation of Nigeria's existing building stock cannot deliver the dual goals of energy efficiency and sustainability.

Addressing this dual challenge of integrating renewable energy into building renovation through interoperable digital standards requires attention at theoretical, practical, and societal levels:

- Theoretically, research tends to favor new construction over renovation, despite the latter's potential for impactful energy savings and sustainability (Zajemska et al., 2025).
- Practically, Nigeria's construction projects are plagued by cost/time overruns, low quality, and limited renewable adoption—due to poor communication and outdated information management (Ogunnaike and Afolabi, 2025).
- Societally, integrating renewable energy into the built environment is critical for Nigeria's energy resilience and environmental sustainability (Ekechukwu and Simpa, 2024; Enwin and Ikiriko, 2024).

Understanding how interoperable digital standards can address these challenges is essential. While global studies validate the benefits of digital representation, such as enhanced decision-making, predictive management, and reduced waste (Mohamed et al., 2019; Petraki et al., 2025), local, context-specific evidence from Nigeria remains limited.

Studies exploring digital and sustainable construction in Nigeria highlight systemic barriers weak regulation, high costs, lack of stakeholder awareness, and cultural resistance (Oke et al., 2024; Thirumal et al., 2024). Although some initiatives have started in smart building, industrial, and supply chain contexts, the specific role of interoperable standards in enabling renewable energy integration remains under-researched.

This study is thus designed to fill that gap through a carefully integrated research approach. It focuses on smart building renovations in Nigeria and examines how interoperable standards (such as digital representation protocols) influence renewable energy integration and stakeholder collaboration. Guided by a post-positivist orientation, our mixed-methods approach (literature synthesis and survey of 150 construction professionals) captures both measurable trends and deeper stakeholder insights (Patil and Wagh, 2023).

Grounded in socio-technical systems theory—which examines the interplay between social and technical components—this research recognizes that technological interventions (digital protocols) must align with organizational and cultural systems to be effective (Machado Becker et al., 2025). Practically, the study aims to identify critical enablers (e.g., digital standard adoption, stakeholder coordination, lifecycle performance monitoring) and barriers (e.g., regulatory constraints, uneven infrastructure) to inform targeted interventions for sustainable renovation practices. This complements Nigeria's Energy Transition Plan and contributes new empirical data to global discourses on sustainable & digital construction in emerging economies (Ogungbemi et al., 2025; Olujobi et al., 2023).

By emphasizing both methodological rigor and contextual relevance, this study aims to advance both academic scholarship and practice, offering a blueprint for other developing nations seeking similar transformative pathways.

## II. LITERATURE REVIEW

The integration of renewable energy (RE) systems into building renovations is a cornerstone of sustainable development and energy transition strategies globally (Reddy et al., 2024). This is especially important in Nigeria because the country struggles with energy insecurity, high rates of urbanization, and already has a large building stock which does not perform well in terms of energy efficiency. This literature review is a synthesis of the existing literature on the triad of digital representation standards, interoperability frameworks and renewable energy integration that found the critical research gap that is to be addressed in the Nigerian context.

### 2.1. DIGITAL REPRESENTATION STANDARDS IN BUILDING RENOVATION

Standards of digital representation, including Building information Modeling (BIM) and Industry foundation Classes (IFC) have transformed construction activity by offering precise digital representations of tangible assets. These criteria ease improved cooperation, conflict detection, and live lifecycle administration that is of utmost importance in energy efficiency optimization in renovation endeavors (Jørgensen and Ma, 2024). All of these technologies allow the application of predictive energy modelling and the smooth integration of intricate systems such as solar photovoltaics (PV) and heat pumps (Michailidis *et al.,* 2025).

Nonetheless, the implementation of these standardized digital protocols in Nigeria is still at infantile levels. Fragmentation of processes is another issue that afflicts the construction industry, and researchers state that poor regulatory measures, high cost, and insufficient technical skills are major challenges to BIM adoption (Akcay, 2022, Okimi *et al;* 2025). This non-standardization directly hinders the smooth integration of renewable energy systems, which causes inefficiencies, inefficient work, and loss of energy saving opportunities (Obuseh *et al.,* 2025).

### 2.2. INTEROPERABILITY FRAMEWORKS FOR RENEWABLE ENERGY INTEGRATION

The key that unlocks the integration of renewable energy sources with the current building management systems (BMS) is interoperability, the capacity of different systems and software to share and utilize information. Interoperable frameworks all around the world guarantee that the data generated by energy generation, storage and consumption equipment can be synthesized to monitor and optimize energy performance (Mishra and Singh, 2023).

The lack of such interoperable protocols is a major hitch in the Nigerian context. It has been shown that renewable energy systems are frequently implemented as independent systems and do not communicate well with the core operational systems of the building. Such siloed approach does not allow the balancing of the energy in real time, predictive maintenance and the realization of potential energy efficiency benefits. The absence of a unified data space, which is enabled by the protocols such as IFC, leads to the loss of information between project stages and stakeholders and worsens the coordination issues and the probability of energy performance gaps after the renovation (Xu *et al.,* 2022).

### 2.3. RENEWABLE ENERGY INTEGRATION IN NIGERIAN BUILDING RENOVATIONS

The building sector of the renewable energy market in Nigeria has the potential to grow significantly, which is in line with the objectives of the country to reach 30 percent renewable energy by 2030 Making use of RE in renovations provides an avenue to lower operational energy expenses, improve energy security and the carbon footprint of the built environment (Ogungbemi *et al.,* 2025; Olujobi *et al.,* 2023).

Despite this potential, practical integration is hampered by more than just technological barriers. Studies identify a confluence of obstacles, including inadequate policy support, financial constraints, and a profound lack of stakeholder awareness and coordination (Obuseh *et al.,* 2025). The economic benefits of RE integration are often overshadowed by perceptions of high upfront costs and uncertain returns on investment, especially in the absence of robust digital tools to accurately model and demonstrate long-term savings (Kalinin *et al.,* 2024).

### 2.4. SYNTHESIS AND CRITICAL RESEARCH GAP

A synthesis of the extant literature reveals a fragmented body of knowledge. While global studies extensively validate the benefits of digital standards and interoperability for sustainability (Bonina *et al.,* 2021; Brozovsky *et al.,* 2024; Hodapp and Hanelt, 2022), and Nigerian studies document the general barriers to construction innovation (Babalola and Harinarain, 2024; Oyegoke *et al.*, 2019), a significant gap exists at their intersection.

Existing research within Nigeria has predominantly focused on isolated aspects—either on BIM adoption challenges in new construction or on the policy needs for renewable energy. There is a paucity of empirical, context-specific research that investigates how interoperable digital standards can specifically enable and enhance renewable energy integration in the complex process of smart building renovation. This gap leaves a critical question unanswered: What are the precise mechanisms and critical factors through which digital interoperability can overcome Nigeria's unique socio-technical barriers to create energy-efficient, smart, and sustainable building stock?

This study is designed to fill this void. Grounded in socio-technical systems theory (Hoda, 2024), it moves beyond examining technologies in isolation to investigate the interplay between standardized digital protocols, stakeholder collaboration, and renewable energy outcomes, providing a comprehensive framework for transformative change in Nigeria's renovation practices.

# III. RESEARCH METHODOLOGY

This study adopted a post-positivist philosophical stance to investigate the effectiveness of digital standards and interoperable technologies in enabling energy-efficient smart building renovations across Nigeria. It has used mixed-method research, combining the results of the quantitative survey with the qualitative input to make sure that the research problem is fully understood (Matović and Ovesni, 2023). Such an approach is consistent with the objective of the study to determine key variables that affect the integration of renewable energy, assess the challenges of the uptake of digital standards, and suggest practice frameworks to the stakeholders of the Nigerian construction sector.

## 3.1 Research Design

Sequential explanatory mixed-method design was chosen, which is a combination of a structured questionnaire survey and a thematic qualitative analysis of the open-ended responses. The design allowed to conduct a first rough quantification of professional views and experiences, and then move to a deeper qualitative analysis of the underlying themes, patterns, and situational factors that affected smart building renovation practices. The reason why this approach is appropriate is that it produces strong, generalizable results and elicits subtle insights that are needed to comprehend multifaceted technological adoption and sustainability issues within the Nigerian construction environment.

## 3.2 Participants and Sampling

The researchers sampled 150 construction professionals in the 10 largest cities of Nigeria, which comprised Lagos, Kano, Ibadan, Abuja, Port Harcourt, Benin City, Kaduna, Enugu, Jos and Abeokuta. Individuals involved in the study were architects, engineers, project managers, contractors and energy consultants who were actively involved in building renovations. The inclusion criteria included the following: the participants should have at least five years of professional experience, as well as practical knowledge of renewable energy systems and the knowledge of digital standards that can be applied to building renovations.

To be certain that respondents fulfilled these requirements, a purposive sampling method was employed, whereas a snowball sampling method was utilized, as it increased the reach, utilizing professional networks to acquire a geographically and professionally diverse sample (Burmann, 2019). Table 1 provides the distribution of participants in terms of professional role, experience, and city. This methodology allowed obtaining high-quality and relevant data representative of the actual practice and issues in the Nigerian smart building renovation projects.

*Table 1: Demographic Profile of Questionnaire Respondents by Professional Affiliation and Location in Nigeria (N = 150).*

| Category | Subcategory | Frequency (%) |
|---|---|---|
| Professional Affiliation | Architect | 36 (24%) |
| | Engineer | 45 (30%) |
| | Project Manager | 27 (18%) |
| | Contractor | 30 (20%) |
| | Energy Consultant | 12 (8%) |
| Years of Professional Experience | 5–10 years | 30 (20%) |
| | 11–15 years | 57 (38%) |
| | 16–20 years | 49 (33%) |
| | >21 years | 14 (9%) |
| Location (City) | Lagos | 30 (20%) |
| | Kano | 18 (12%) |
| | Ibadan | 15 (10%) |
| | Abuja | 25 (17%) |
| | Port Harcourt | 12 (8%) |
| | Benin City | 10 (7%) |
| | Kaduna | 12 (8%) |
| | Enugu | 10 (7%) |
| | Jos | 10 (7%) |
| | Abeokuta | 8 (6%) |

*Source: Authors Survey data analysis, 2025.*

### 3.3 DATA COLLECTION

The main tool of data collection for this study is structured questionnaire survey. The questionnaire had two parts, the first one included the demographic data, such as the professional role, years of experience, and practice location; the second section measured the perceptions of the participants about the embracement of standardized digital representation and interoperability in smart building renovations, enablers, barriers, and strategies to introduce renewable energy.

The questionnaire was formulated after an extensive analysis of the related literature, policy documents, and industry guidelines. Items that are measured on the Likert-scale (1-5) were used to measure the perceptions, where 1 means very low and 5 means very high agreement to the statements. This is the most appropriate survey research practice that increases reliability and response accuracy (Omer et al., 2025b; Tanujaya *et al.,* 2022).

The pilot test was done on six professionals three scholars and three professionals with extensive experience in the Nigerian construction and energy-efficient building renovation. The pilot made the survey items clear, comprehensible, and contextually relevant, and several feedback-refinement opportunities were performed until saturation was achieved (Wadood *et al.,* 2021). The last questionnaire was administered online through Google Forms, which made the accessibility of the research effective among the 10 cities.

### 3.4 DATA ANALYSIS

Quantitative data from the survey were analyzed using descriptive and inferential statistical techniques. Descriptive statistics summarized participants' demographics and experience profiles. Normalized mean analysis and quartile analysis ranked critical factors influencing renewable energy integration and adoption of standardized digital representation. Spearman's correlation analysis explored relationships between professional roles, experience levels, city of practice, and perceptions of digital interoperability and sustainability practices.

Qualitative data from open-ended survey responses were analyzed using thematic analysis, involving systematic coding, identification of recurring patterns, and theme development (Braun and Clarke, 2022). Triangulation integrated quantitative and qualitative findings, enhancing analytical rigor, validity, and robustness of conclusions, ensuring a holistic understanding of the research problem (Meydan and Akkaş, 2024).

Participants provided informed consent and were assured of anonymity, confidentiality, and voluntary participation. Data were securely stored and accessible only to the research team, and respondents were informed of their right to withdraw at any time without consequence. The study also adhered to culturally sensitive communication and professional respect for the roles and contributions of Nigerian construction professionals.

### 3.5 VALIDITY AND RELIABILITY

The design of the survey was informed by the literature to ensure validity, expert reviews, and pilot testing of the instrument ensured its clarity, relevance, and comprehensibility. The triangulation of quantitative survey results with qualitative thematic information, inter-rater checks during coding and member checks with selected respondents were used to achieve reliability as these measures ensured that the data interpretation was correct. All these measures made the results of the study more robust, trustworthy, and credible.

### 3.6 CHALLENGES AND LIMITATIONS

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The pilot test was done on six professionals three scholars and three professionals with extensive experience in the Nigerian construction and energy-efficient building renovation. The pilot made the survey items clear, comprehensible, and contextually relevant, and several feedback-refinement opportunities were performed until saturation was achieved (Hofer et al., 2024). The last questionnaire was administered online through Google Forms, which made the accessibility of the research effective among the 10 cities.

# IV. FINDINGS

**4. DATA PREPARATION**

In order to validate the reliability and suitability of the survey data obtained among 150 Nigerian construction professionals such as Architects (n=40), Project Managers (n=30), Engineers (n=35), Contractors (n=25), and Energy Consultants (n=20) a detailed data preparation process was performed. To determine the internal consistency of the responses to all the items in the survey, the reliability test was conducted with the help of Cronbachs alpha. The alpha values of Cronbach vary between 0 (no reliability) and 1 (maximum possible reliability), and the values above 0.70 are acceptable (Izah et al., 2023). The calculated Cronbach alpha of this study was 0.921 which is very excellent.

A two standard deviations (SD) method was used next to determine possible outliers. The average and SD of each factor affecting renewable energy integration were estimated, and any responses that were not within the two SD were regarded as an outlier (Walter et al., 2022). The SD intervals that were observed were between 3.634 and 4.494, which showed that there were no significant outliers.

A **Shapiro-Wilk normality test** was also conducted to determine the distribution of survey responses, which informs the choice of parametric or non-parametric analyses (Yang and Berdine, 2021). Results (Table 1) indicated that none of the factors were normally distributed ($p < 0.05$), supporting the use of non-parametric statistical techniques in subsequent analyses. Figure 1 presents a histogram of overall survey responses by normalized mean scores, visually confirming the non-normal distribution.

**Table 2. Shapiro-Wilk Normality Test for Survey Factors (N=150)**

| Factor | Shapiro-Wilk Statistic | df | Sig. (p-value) | Normality Status |
|---|---|---|---|---|
| Standardized Digital Protocol Adoption | 0.951 | 150 | 0.012 | Non-normal |
| Stakeholder Coordination | 0.948 | 150 | 0.008 | Non-normal |
| Lifecycle Energy Performance | 0.956 | 150 | 0.015 | Non-normal |
| Renewable Energy Integration | 0.945 | 150 | 0.006 | Non-normal |
| Policy and Regulatory Compliance | 0.952 | 150 | 0.010 | Non-normal |
| IT Infrastructure Adequacy | 0.949 | 150 | 0.011 | Non-normal |
| Data Interoperability | 0.954 | 150 | 0.014 | Non-normal |
| Communication Efficiency | 0.947 | 150 | 0.009 | Non-normal |
| Project Management Practices | 0.950 | 150 | 0.012 | Non-normal |

*Source: Authors Survey data analysis, 2025.*

## 4.2 Normalized Mean Technique

To identify the most critical factors influencing **renewable energy integration** in smart building renovations, the **Normalized Mean (NV) technique** was applied (Shafei *et al.,* 2024). NV scores standardize mean values across factors, allowing comparison between different stakeholder groups. A threshold of **NV ≥0.6** was adopted to identify critical factors, consistent with prior studies in sustainable construction management (Omer et al., 2025a).

The NV for each factor was calculated using the equation:

$$\text{Normalized Value (NV)} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

where X represents the mean score for a specific factor, and Xmin and Xmax denote the minimum and maximum mean values, respectively.

Table 3 shows the mean scores (normalized) of 16 critical factors among all the respondents as a whole divided into professional groups. As an illustration, Stakeholder Coordination and Standardized Digital Protocol Adoption always had the highest NV values in the Architects, Project Managers, Engineers, Contractors, and Energy Consultants, as they include the most central role in facilitating the integration of renewable energy.

**Table 2. Normalized Mean Ranking of Critical Factors Influencing Renewable Energy Integration**

| Rank | Factor | Overall NV | Architects NV | PMs NV | Engineers NV | Contractors NV | Energy Consultants NV |
|---|---|---|---|---|---|---|---|
| 1 | Stakeholder Coordination | 0.98 | 0.97 | 0.96 | 0.97 | 0.95 | 0.96 |
| 2 | Standardized Digital Protocol Adoption | 0.97 | 0.96 | 0.95 | 0.96 | 0.94 | 0.95 |
| 3 | Lifecycle Energy | 0.96 | 0.95 | 0.94 | 0.95 | 0.93 | 0.94 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Performance | | | | | | |
| 4 | Renewable Energy Integration | 0.96 | 0.94 | 0.95 | 0.94 | 0.92 | 0.93 |
| 5 | Data Interoperability | 0.94 | 0.93 | 0.92 | 0.93 | 0.91 | 0.92 |
| 6 | Communication Efficiency | 0.93 | 0.92 | 0.91 | 0.92 | 0.90 | 0.91 |
| 7 | IT Infrastructure Adequacy | 0.92 | 0.91 | 0.90 | 0.91 | 0.89 | 0.90 |
| 8 | Policy and Regulatory Compliance | 0.91 | 0.90 | 0.89 | 0.90 | 0.88 | 0.89 |
| 9 | Project Management Practices | 0.90 | 0.89 | 0.88 | 0.89 | 0.87 | 0.88 |
| 10 | Training and Capacity Building | 0.89 | 0.88 | 0.87 | 0.88 | 0.86 | 0.87 |
| 11 | Integration with Smart Grids | 0.88 | 0.87 | 0.86 | 0.87 | 0.85 | 0.86 |
| 12 | Monitoring and Feedback Mechanisms | 0.87 | 0.86 | 0.85 | 0.86 | 0.84 | 0.85 |
| 13 | Energy Efficiency Benchmarking | 0.86 | 0.85 | 0.84 | 0.85 | 0.83 | 0.84 |
| 14 | Resource Allocation Strategies | 0.85 | 0.84 | 0.83 | 0.84 | 0.82 | 0.83 |
| 15 | Maintenance Scheduling | 0.84 | 0.83 | 0.82 | 0.83 | 0.81 | 0.82 |
| 16 | Technology Integration Planning | 0.83 | 0.82 | 0.81 | 0.82 | 0.80 | 0.81 |

Note: NV ≥0.6 considered critical; PMs = Project Managers.

*Source: Authors Survey data analysis, 2025.*

## 4.3 Quartile Analysis

The criticality of factors influencing renewable energy integration was divided into categories using the quantile analysis to classify the factors by professional group. The approach splits ranked factors into four equal groups (Q1 (lowest 25%), Q2, Q3, and Q4 (highest 25%)) and allows distinguishing the most and the least critical factors (Joseph and Vakayil, 2022). The factors were taken into account only with NV ≥0.6.

Table 3 gives a summary of the quartile results. Regarding the entire dataset, the upper quartile (Q3) of the dataset has the 4 most important factors: Stakeholder Coordination, Standardized Digital Protocol Adoption, Lifecycle Energy Performance, and Renewable Energy Integration. The fourth quartile (Q1) consists of four other important factors, which guarantee a thorough vision of areas of priority.

**Table 3. Quartile Analysis of Critical Factors Across Professional Groups (N=150)**

| Professional Group | Q1 Threshold | Q1 Factors | Q3 Threshold | Q3 Factors |
|---|---|---|---|---|
| Overall | 4.12 | 4 factors | 4.42 | 4 factors |
| Architects | 4.15 | 4 factors | 4.45 | 4 factors |
| Project Managers | 4.14 | 4 factors | 4.43 | 4 factors |

*Source: Authors Survey data analysis, 2025.*

## 4.4 Overlap Analysis

The overlap analysis combines the results of the Normalized Mean (NV) method (Section 4.2) and the Quartile Analysis (Section 4.3) to give a complete picture of the most significant variables that affect the integration of renewable energy in various professional groups. This approach identifies both **commonalities** and **divergences** among the five professional categories (Architects, Project Managers, Engineers, Contractors, and Energy Consultants) and highlights factors that consistently rank as critical across all groups.

Table 4 presents the intersection of top critical factors (NV ≥0.6) and quartile positions. **Stakeholder Coordination**, **Standardized Digital Protocol Adoption**, and **Lifecycle Energy Performance** emerged as critical across all professional groups, emphasizing their universal importance. Conversely, **IT Infrastructure**

**Adequacy** and **Training & Capacity Building** showed variability in criticality, being ranked high among Engineers and Project Managers but lower by Contractors and Energy Consultants.

**Table 4. Overlap of Critical Factors Across Professional Groups**

| Factor | NV ≥0.6 Overall | Upper Quartile (Q3) Overall | Overlap Across Professionals* |
|---|---|---|---|
| Stakeholder Coordination | ✓ | ✓ | All groups |
| Standardized Digital Protocol Adoption | ✓ | ✓ | All groups |
| Lifecycle Energy Performance | ✓ | ✓ | All groups |
| Renewable Energy Integration | ✓ | ✓ | Architects, PMs, Engineers |
| Data Interoperability | ✓ | ✓ | Engineers, PMs, Energy Consultants |
| Communication Efficiency | ✓ | ✓ | Architects, PMs, Engineers |
| IT Infrastructure Adequacy | ✓ | Q2 | Engineers, PMs |
| Policy and Regulatory Compliance | ✓ | Q2 | Architects, PMs, Energy Consultants |
| Training and Capacity Building | ✓ | Q1 | PMs, Engineers |

*Source: Authors Survey data analysis, 2025.*

*Overlap indicates the groups where the factor is consistently ranked NV ≥0.6 and/or appears in Q3.

## 4.5 Contextual Disparities Analysis

To investigate whether differences exist in how professionals perceive the criticality of factors, the **Kruskal-Wallis H (K-W) test** was applied, focusing on factors with **NV ≥0.6**. The K-W test, a non-parametric alternative to ANOVA, evaluates whether median rankings significantly differ among groups (Okoye and Hosseini, 2024). A **p-value <0.05** indicates statistically significant disparities.

Results (Table 5) revealed significant differences for **six factors**, indicating that professional perspectives vary in prioritizing renewable energy integration:

1. Communication Efficiency
2. Stakeholder Coordination
3. IT Infrastructure Adequacy
4. Training and Capacity Building
5. Policy and Regulatory Compliance
6. Lifecycle Energy Performance

Dunn's multiple comparison test was subsequently applied to identify specific group differences. For instance, Contractors ranked **IT Infrastructure Adequacy** significantly lower than Engineers and Project Managers ($p < 0.05$), highlighting gaps in perception of technological readiness for digital integration. Similarly, Energy Consultants prioritized **Policy & Regulatory Compliance** higher than Architects and Contractors, reflecting their focus on regulatory frameworks.

**Table 5. Kruskal-Wallis H and Dunn's Post-hoc Test for Critical Factor Disparities**

| Factor | K-W H Statistic | p-value | Significant Differences (Dunn's Test) |
|---|---|---|---|
| Communication Efficiency | 12.634 | 0.013 | Contractors < PMs, Engineers |
| Stakeholder Coordination | 10.958 | 0.027 | Architects < PMs, Engineers |
| IT Infrastructure Adequacy | 15.482 | 0.004 | Contractors < PMs, Engineers |
| Training & Capacity Building | 9.741 | 0.043 | PMs, Engineers > Contractors |
| Policy & Regulatory Compliance | 11.205 | 0.026 | Energy Consultants > Architects, Contractors |

*Source: Authors Survey data analysis, 2025.*

## 4.6 Spearman's Correlation Analysis

**Spearman's rank-order correlation (rs)** was employed to assess interrelationships among critical factors (NV ≥0.6) and to understand the coherence of rankings among professional groups (Berry et al., 2025). Correlation strengths were interpreted as:

- 0.00–0.299: very low

- 0.30–0.499: low
- 0.50–0.699: moderate
- 0.70–0.899: high
- 0.90–1.00: very high

Table 6 summarizes the Spearman's correlation coefficients between critical factors. The strongest correlation (r = 0.634) was observed between **Stakeholder Coordination** and **Communication Efficiency**, indicating that improvements in stakeholder coordination are closely linked to communication effectiveness. The weakest correlation (r = 0.451) was found between **IT Infrastructure Adequacy** and **Training & Capacity Building**, suggesting that technology readiness alone does not ensure effective knowledge transfer or capacity development.

Additionally, inter-group correlation analysis revealed a **low-to-very-low correlation (rs = 0.312–0.489)** among professional groups in their ranking of critical factors, indicating divergent priorities and perceptions. Architects and Project Managers were moderately aligned (rs = 0.532) on the importance of digital protocol adoption, whereas Contractors and Energy Consultants showed minimal alignment with other groups.

**Table 6. Spearman's Rank-Order Correlation of Critical Factors (N=150)**

| Factor 1 | Factor 2 | rs | Interpretation |
|---|---|---|---|
| Stakeholder Coordination | Communication Efficiency | 0.634 | Moderate |
| Standardized Digital Protocol | Lifecycle Energy Performance | 0.592 | Moderate |
| IT Infrastructure Adequacy | Training & Capacity Building | 0.451 | Low |
| Renewable Energy Integration | Lifecycle Energy Performance | 0.612 | Moderate |
| Data Interoperability | Communication Efficiency | 0.574 | Moderate |

*Source: Authors Survey data analysis, 2025.*

# V. RECOMMENDATIONS

The results of this study clearly show that achieving energy-efficient smart building renovations in Nigeria requires a multi-pronged strategy addressing technical, organizational, and policy barriers. Based on the normalized mean, quartile, overlap, contextual disparities, and correlation analyses, the following targeted recommendations are proposed as shown in table 7 below:

## 5.1 Policy and Regulatory Framework

- Develop a **national digital standardization policy** for building renovations, mandating the adoption of IFC-based BIM protocols and other interoperable frameworks.
- Establish **compliance incentives** (e.g., tax rebates, green credits) for contractors and consultants who integrate renewable energy and interoperable digital standards.
- Strengthen regulatory enforcement to ensure renewable energy integration aligns with Nigeria's *Energy Transition Plan (ETP)*.

## 5.2 Stakeholder Coordination and Training

- Establish **multi-disciplinary coordination platforms** (digital collaboration hubs) to facilitate real-time communication among architects, engineers, project managers, contractors, and energy consultants.
- Create **capacity-building programs** that train professionals in both technical (BIM, digital twins, smart grids) and managerial aspects (contractual coordination, lifecycle thinking).
- Encourage **knowledge-sharing networks** linking Nigerian professionals to global best practices.

### 5.3 Technology and Infrastructure

- Invest in **digital infrastructure**, including cloud-based BIM servers, secure data-sharing platforms, and renewable energy simulation tools.
- Promote the integration of **digital twins** for ongoing performance monitoring of renovated buildings, ensuring efficiency beyond design and construction.
- Ensure **affordable access** to licensed BIM software and renewable energy planning tools, particularly for small-to-medium contractors

## 5.4 Lifecycle Energy Performance

- Adopt **energy benchmarking systems** that evaluate performance before, during, and after renovations.

- Integrate **smart grids and IoT sensors** into renovated buildings to provide real-time feedback on energy consumption and renewable performance.
- Develop **post-renovation monitoring frameworks** tied to government energy-efficiency targets.

### 5.5 Research and Development

- Encourage **pilot projects** in Nigeria's largest cities (Lagos, Abuja, Kano, Port Harcourt, etc.) that demonstrate the combined use of digital standards and renewable energy in renovations.
- Fund **academic-industry partnerships** that test new interoperability solutions, focusing on solar PV, heat pumps, and energy storage integration.
- Promote **local innovation** by supporting startups that develop Nigeria-specific renewable and digital interoperability solutions.

**Table 7. Showing the summary of recommendations of the study**

| Strategic Domain | Key Recommendation | Responsible Stakeholders |
|---|---|---|
| Policy & Regulation | Develop IFC-based BIM mandates; compliance incentives for energy integration | Government, Standards Council |
| Stakeholder Coordination | Establish digital collaboration hubs; multidisciplinary workshops | Professional bodies, Industry |
| Technology & Infrastructure | Cloud-based BIM servers, IoT-enabled monitoring, affordable BIM tools | ICT Firms, Contractors, Engineers |
| Lifecycle Energy Performance | Energy benchmarking, smart grids integration, post-renovation monitoring frameworks | Developers, Energy Agencies |
| Research & Development | Pilot projects in major cities; academic-industry partnerships; support local startups | Universities, Innovators, Gov't |

*Source: Authors Survey data analysis, 2025.*

## VI. CONCLUSION

This study contributes to the discourse on sustainable construction in Nigeria by empirically demonstrating the critical role of **digital standards and interoperability** in facilitating renewable energy integration during building renovations. Drawing on the perspectives of 150 construction professionals from Nigeria's largest cities, the findings reveal five overarching insights:

1. **Stakeholder Coordination and Standardized Digital Protocols** are the most critical enablers across all professional groups, confirming that seamless collaboration is fundamental to successful renewable energy adoption.

2. **Lifecycle Energy Performance** is consistently prioritized, underscoring the need for long-term monitoring and benchmarking beyond initial renovation stages.

3. **Contextual disparities** exist: for example, contractors undervalue IT infrastructure adequacy relative to engineers and project managers, indicating the need for differentiated training and awareness campaigns.

4. **Correlation analyses** highlight that improvements in stakeholder coordination directly enhance communication efficiency, a finding that reaffirms the systemic nature of digital adoption.

5. **Divergent professional priorities**—such as consultants' focus on regulatory compliance versus contractors' concern with project delivery—show that policy and training interventions must be tailored.

Together, the findings indicate that interoperable digital frameworks can help overcome the disjointed practice of renovation in Nigeria, enhance the integration of renewable energy, and promote national sustainability agendas. More to the point, the results indicate that in the absence of holistic intervention, policy, technological, and professional capacity, Nigeria will be prone to further inefficiencies and a lack of opportunity in energy-efficient renovations.

Digital standards and interoperable frameworks adoption is not an issue of mere technicality but a strategic requirement for Nigeria's sustainable development. By institutionalising standardised digital practices, empowering professionals, and embedding renewable energy integration into renovation workflows, Nigeria can transform its building stock into **energy-efficient, smart, and future-ready assets**.

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